Abstract:

With increasing population and per-capita capita waste generation, cities in India and other developing countries are seeking alternative strategies to manage the organic fraction of municipal solid waste in an effort to improve efficiency, reduce costs, and increase environmental performance. This work aims to explore the tradeoffs of various organic waste management strategies in the urban Indian context, specifically using a case study analysis of the waste system in the city of Pune. Door-to-door, primary, and secondary collection and four technologies for treating organics (landfilling, composting, anaerobic digestion, and pelletization) are analyzed with regard to cost and environmental performance. Because decentralized waste system architectures minimize transportation and allows wastepickers to maintain jobs, particular emphasis is made in this project to understand the cost and environmental implications treatment at a range of scales.

To determine the quantity and composition of waste, we conducted waste audits of MSW that was collected from 2,650 households during two different seasons. Per-capita MSW generation in Pune was found to be 134, 309, and 401 grams/day for the lower, middle, and upper income residents, respectively. Of these totals, 80%, 66%, and 69% of the MSW was biodegradable. Given that middle and upper income residents generate 2.3 to 3 times what lower income residents generate, India can expect to see a significant increase in waste volumes as its population becomes wealthier.

By comparing the spatial footprints of the technologies at a range of scales, it was found that pelletization of organic MSW (although it is not a fully developed technology) has great potential to reduce the spatial footprint of organic waste management.

Cost modeling is used to identify the drivers of cost for each process and to identify the least-cost options. The cost per ton of waste managed using anaerobic digestion, composting, and pelletization decreases significantly with larger scale of treatment. Alternative organics management technologies used at small scales (less than 0.5 TPD) are more expensive than landfilling; however, if a facility of at least 0.5 TPD is used, anaerobic digestion is less expensive than landfilling. Pelletization and composting become less expensive than landfilling at the scale of 5 TPD and 200 TPD, respectively. Although the average cost of centralized organic waste systems is lower, the difference in cost between the lowest-cost decentralized systems and lowest-cost centralized systems was relatively small.

A review of the relevant literature is used to identify the global warming impacts of organic waste processing. The global warming potential (GWP) of anaerobic digestion, pelletization, composting, and landfilling is estimated to be -51, -42, 38, and 510 kg CO₂-eq/ton, respectively. A city looking to minimize its contribution to global warming could achieve significant reductions in emissions by biodigesting food waste and pelletizing yard waste. Such systems would have a net greenhouse gas emissions savings of over 750 tons CO₂-eq each year.

Of the technologies assessed, anaerobic digestion (at scales of 5 TPD or larger) has the best combination of cost and GWP performance. However, because woody material cannot be digested, pelletization (at 10 TPD plants) has the best combination of cost and GWP performance specifically for handling yard waste. These findings suggest that for handling organic MSW, anaerobic digestion in combination with pelletization produces the best combination of cost and GWP performance.
1. Introduction

Cities within the developing world face increasing volumes of municipal solid waste (MSW) and limited budgets and space for managing the waste. Urban waste management in India requires special attention given the magnitude of waste being generated, the demographic shift and population growth, the size of the informal sector, and the large organic fraction of waste. In India, population growth, especially in cities, is putting pressure on the capacity and function of waste infrastructure; more waste is being generated per square kilometer than ever before. Moreover, as India experiences upward mobility and a growing middle class, city residents are consuming more and disposing of more, driving up per-capita waste generation. The city of Pune, India spends over 11 million USD (71 Crore Rupees) on solid waste management – collection, processing, and disposal – each year (Times of India, 2012). Indian cities are seeking new strategies to manage MSW in an effort to improve efficiency, reduce costs, and attain environmental standards.

One of the most challenging MSW streams in urban India is biodegradable waste (food and yard waste). In India, organic waste often ends up in open-air dump sites, which has negative environmental impacts on climate change and water quality. Landfilling organic waste also has created political tension and protests by residents living nearby, who are most impacted by acute pollution and landfill fires. Current organic waste management practices in India not only raise problems and costs, but also do not take fully utilize the material as a resource. Organic waste is rich in nutrients and can be processed for the production of energy or valuable end-products; this report focuses on four treatment methods that can be used for organic waste: landfilling, composting, anaerobic digestion, and pelletization. Improved management of organic waste would divert significant amounts of waste from landfills, provide the potential for additional value creation, minimize the spatial footprint, and increase nutrient cycling.

2. Objectives and Research Question

This project aims to explore the tradeoffs of various organic waste management strategies in the urban Indian context. Specifically, it uses environmental and economic metrics to quantify and characterize the impacts of organic waste management; it also uses qualitative social and labor indicators to assess the impacts of waste management on stakeholders. Stages of collection and technologies for treating organics are analyzed using these metrics. Particular emphasis is made to understand the implications of the scale of treatment, given that this can impact cost-effectiveness, environmental burden, and social acceptability. Using decentralized system architectures for waste management is beneficial in that it enable effective manual segregation, maintain jobs for wastepickers, manage the health exposure risks, and minimize transportation. This project aims to test the hypothesis that there are decentralized waste system architectures that can improve on the economic and environmental performance of organic waste management systems. This project aims to answer the question, what are the characteristics of a decentralized system that:

1. Is appropriate for the quantity and composition of waste generated in urban Indian?
2. Is cost-effective collecting and treating organic waste?
3. Reduces global warming impact (i.e., greenhouse gas emissions)?
4. Impacts stakeholders, including the informal sector, positively?

3. General Approach and Structure

In order to answer the above question, I use a multi-pronged analysis that looks at the economic, environmental, and social impacts of waste management in order to identify sustainable organic waste management. I have applied these analyses to the case study of one of India’s largest
cities, Pune. Through the use of one city as a case study, I am able to use primary data, conduct in-depth analysis of scenarios, and provide useful results to decision makers in India.

I use interviews, personal observations, and literature review to understand the historical and political context of waste management in the city. I also use stakeholder analysis to understand incentives, needs, and constraints on the system and its actors. I use materials flow analysis to map municipal waste streams from generation to treatment. Additionally, I use the empirical results of two waste audits to analyze the quantity and composition of waste as a function of income and seasonality. Cost modeling is used to identify the drivers of cost for various technologies and processes and to identify the least-cost options. A review of the relevant literature is used to identify the global warming impacts of organic waste processing. And stakeholder perspectives on the waste management system and its future direction were obtained by hosting a workshop and conducting surveys.

4. Municipal Solid Waste Quantity and Composition

4.1 Waste Generation and Processing Volumes

Due to the complexity of the waste management system within Pune and the lack of aggregated data on generation and processing, mapping the flows of waste throughout the entire city required aggregation of multiple data sources from the Pune Municipal Corporation (PMC), interviews, and publications. The majority of MSW (about 72%) comes from residential waste, with all forms of commercial waste (hotel and restaurant, produce, and other businesses) making up 12% of the city’s waste. The bulk of biodegradable waste is sent to the two centralized compost facilities, the biogas plants, or the landfill. Based on data from interviews and literature, Pune generates about 1,666 tons of MSW per day. We estimate that 400 of these tons are landfilled, 323 tons of recyclable material is recycled, 450 tons of mixed waste used to for gasification and RDF, and that 442 tons of biodegradable waste is composted or digested. In mapping these flows, the most challenging figure to verify was the amount of waste sent to the landfill, as the city does not openly share this figure. The estimate of 400 tons/day was calculated using the estimate that 1,666 tons/day of waste are generated in the city, and all but 47 tons of this are collected and processed.

4.2 Important Characteristics of the Pune Waste System

Pune’s waste management logistics are complex in that the waste from 15 administrative wards is sent to large number of treatment sites, which are operated and owned by a number of different companies and organizations. The city has a wide range of waste processing facilities, including 2 TPD mechanical composting plants, 5 TPD biogas plants, and 200 TPD vermicomposting sites. Furthermore, Pune’s waste collection and processing system truly is a collaborative effort between the informal and formal sectors. Since 2008, after much activism and a long process of negotiation, the city has had a formal partnership with the waste picker cooperative, SWaCH, and has authorize wastepickers to do door-to-door waste collection. Waste pickers are an integral part of the waste system in Pune (as is true in other Indian cities), the urban poor must be considered in designing Indian waste management solutions.
Given that some residents and businesses still mix biodegradable waste with refuse and the city still sends a significant amount of biodegradable waste to the unlined landfill, Pune’s current management of organic MSW needs improvement. Current practices do not meet regulations on source segregation and processing, nor do they meet the city’s goal of sending zero-waste to the landfill. Given that the largest (by mass) component of MSW going to the landfill is biodegradable, the interests of many stakeholders could be met by using alternative treatment methods for managing organics. Pune is using a number of waste processing methods, but the city does not have a strategic long-term plan for achieving its goal of “zero waste.” The city would benefit from systematic analysis of waste management options, so that it could get closer to truly closing the landfill.

Although the city keeps some records on total incoming waste volumes to some facilities, its data on the quantity and composition of waste generated in Pune is undetailed and limited. The quantities of waste reported are round numbers, and the composition descriptions given are only “biodegradable” or “mixed.” A waste audit needs to be conducted to better determine the characteristics of the city’s waste.

4.3 MSW Quantity, Composition, and Socio-economic Drivers

To empirically determine the volumes of each category of residential waste generated, we conducted a waste audit of residential MSW. The waste audit was carried out by researchers from MIT and the Imperial College of London in conjunction with the waste picker organizations KKPKP and SWaCH. Other methods were used to estimate the quantity of commercial waste generated. The residential audit involved first selecting a number of neighborhoods (known as “societies”) that represent various socioeconomic groups and doing a population count number of residents in that neighborhood. Over two seasons, we sampled waste from a total of 17 different neighborhoods (4 lower income, 8 middle income, and 5 upper income neighborhoods). Most of the neighborhoods had between 50 and 300 homes. For each neighborhood we collected all the residential waste (from doorsteps of houses), sorted and weighed this waste, and finally divided total generation by population to determine per-capita generation. The waste was sorted into the 47 categories by the waste pickers (with the guidance of the supervisor and visual guide). Among the 47 categories were food scraps, yard waste, various types of paper, various types of plastic, multilayer packaging, various types of metal, various types of glass, clothing, sanitary waste, and electronics. Once I obtained per-capita generation values, I could combine this information with the city or the ward’s population to estimate total generation in tons.

The Majority of Residential Waste is Biodegradable

Most of this MSW (at least 65%, and often more) is wet, biodegradable organic waste. The next largest waste streams are paper and plastic. For all socioeconomic groups, the majority of waste was biodegradable material, rather than recyclable or refuse. This is made apparent by the green portion of the bars in Figure 1; in this figure, the biodegradable material category includes food and vegetable matter, recyclables include paper, plastic, metal, and glass, and refuse includes multilayer packaging, clothing, sanitary waste, electronics, and other miscellaneous items. The lower income waste had the highest proportion of biodegradables; it was composed of 80% biodegradables.
Figure 1: Daily per-capita generation of biodegradable, recyclable, and refuse material.

Residential Generation Increases with Income
As is consistent with previous studies, this study found that per-capita waste generation increases with increasing income. The waste audit results indicate that per-capita MSW generation in Pune is 134, 309, and 401 grams/day for the lower, middle, and upper income residents, respectively. The middle income residents generate 2.3 times what lower income residents generate, and upper income residents generate 3 times what lower income residents generate. The widest gap in waste generation exists between the lower income and middle income groups; the middle and upper income groups’ figures followed the trend, but were closer in value. Per-capita generation of almost every type of MSW category increases with increasing income; this trend would imply that Indian cities will be facing an increasing load of MSW as demographics shift to a larger middle class.

Future Wealth Growth will Place Increasing Pressure on the Waste System
Given that the waste audit data clearly shows that higher income populations generate significantly more waste, India can expect to see a significant increase in waste volumes as its population becomes wealthier (Ernst & Young, 2013). As the lower income bracket shrinks and the middle income bracket expands, the percentage of the population generating waste at the middle level will increase, thereby increasing total waste generation. The per-capita generation findings suggest that if 10% of the population moves from the lower-income group to the middle-income group, this would increase total waste generation by 8%.

There are Some Seasonality Differences
By conducting the waste audit in summer as well as winter in Pune, we were able to compare the volume and composition of waste generated by season. Most trends regarding composition and a positive relationship between generation and income hold for both seasons. The composition of each waste stream in terms of percentage is comparably similar for each season. It does appear that there is a greater amount of multilayer packaging generated in summer. With regard to per-capita waste volumes, the winter (February 2015) audit shows that the volumes of waste were larger than in July of 2014 for the lower and upper income residents; this may be a result of higher seasonal consumption or the fact that the set of neighborhoods sampled were slightly different for the two audits.

Sanitary Waste Generation Increases with Income
Lower income residents produced almost no sanitary napkin waste, and only very little diaper waste (totalling 1 g/day). Upper income residents, on the other hand, generated 17 times that amount
(17 g/day) of sanitary waste. Of all of the waste streams, sanitary waste generation was most sensitive to income such that higher income was associated with the largest factor of increase in volumes.

Total Generation Volumes of Residential MSW – Pune City and Aundh Ward

Using the per-capita generation values from the waste audit results above in combination with Pune population estimates, the total volumes of residential MSW generated in Pune was estimated. These values are shown in Table 1. In Figure 2, two pie charts show the breakdown of Pune’s residential MSW by material type versus by economic value. The economic value of a particular stream was found by multiplying the mass by the stream by the selling price (per mass) within the recycling market. It can be seen that even though plastic constitutes less than 6% of the mass, it contributes 60% of the economic value of MSW in the recycling market.

Specifically, for one of Pune’s wards, Aundh, we estimated the commercial generation of organic waste, in addition to the residential generation. Our findings indicated that Aundh generates 7.7 tons/day of commercial organic waste from sources such as hotels, restaurants, and markets. Aundh ward generates roughly 39.8 tons/day of residential organic waste, of which 35.8 tons is food waste and 4.1 is garden and other types of organic waste. In total, we estimate Aundh generates 47.5 tons of organic MSW daily. These waste generation volumes are used to do a ward-specific analysis is Section 8.

Table 1: The socio-economic distribution of Pune’s population and the respective generated volumes of MSW.

<table>
<thead>
<tr>
<th>Socioeconomic Group</th>
<th>Percentage of Population</th>
<th>2014 Population</th>
<th>MSW Generation (Tons/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Income</td>
<td>37%</td>
<td>1,717,958</td>
<td>230</td>
</tr>
<tr>
<td>Middle Income</td>
<td>48%</td>
<td>2,228,702</td>
<td>689</td>
</tr>
<tr>
<td>Upper Income</td>
<td>15%</td>
<td>696,469</td>
<td>279</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100%</td>
<td>4,643,130</td>
<td>1,198</td>
</tr>
</tbody>
</table>

Figure 2: Pie charts showing Pune’s MSW by percentage of total mass and by percentage of total economic value, based on waste audit data and 2014 scrap prices provided by SWaCH.
5. Social and Labor Impacts

This section seeks to understand how the current waste management systems and potential alternative systems impact various stakeholders. Particular emphasis is placed on characterizing the impacts waste management technologies have on the labor force (both formal and informal). Given that waste management in India combines work from both the informal and formal sectors, waste management issues have involved social and labor activism and political conflict. It is important to explore the source of these tensions and challenges. We identify specific strengths and weaknesses of the waste management system from the view of waste sector workers, as well as residents receiving waste services.

- A review of the literature was conducted to identify the types and severity of occupational and health risks of various waste management practices that are relevant to managing the organic fraction of municipal solid waste. The literature review indicates that waste sector workers are vulnerable to health and occupational risks if not provided adequate safety equipment. The literature review indicates that, compared to other organic waste treatment strategies, landfilling and incineration have the most harmful health impacts on residents.
- We also gained insight on social and labor impacts through a stakeholder workshop. The stakeholder workshop discussions illustrated that wastepickers, activists, and academics strongly believe that an organic waste system inclusive of the informal sector must involve decentralized processing and incentives for source segregation of organics.
- Interviews with waste pickers on various aspects of quality of life indicate that wastepickers suffer from relatively poor quality of housing, health, and living environment. However, wastepickers report a relatively high quality of education, community support, safety, and overall life satisfaction. Interviews with itinerant buyers on various aspects of quality of life indicate that itinerant buyers are not receiving adequate education and community engagement.
- Interviews with residents in a diversity of communities the level of awareness about the waste system does affect the degree to which people cooperate with the system. Wealth positively correlated with most qualities, which suggests that the waste management system is most functional in wealthier communities, and requires attention in poorer neighborhoods. The findings of interviews with residents of various socioeconomic groups indicate that slums (as compared to wealthier neighborhoods) experience the lowest quality waste management services in Pune.

6. Economic Analysis

In this section, I analyze the costs and revenues from various practices involved with organic waste management at a range of plant scales. Below, I have determined the net cost per ton of waste managed for door-to-door collection, primary collection, secondary collection, landfilling, composting, anaerobic digestion, and pelletization. In order to do this cost analysis, I developed bottom-up cost models in Excel. These models all represent the costs within the city of Pune, which controls for location-specific factors and policies. Although the specific data used in the model comes from Pune, the results of the models are likely applicable to other cities in India.

To create the models, I used data from waste processing facilities in Pune, which I obtained through interviews, site visits, and official documents. This information was collected in the form of paper documents, digital documents, and personal interviews during the period of August 2013 through August 2015 in Pune, India. These primary sources of information were: SWaCH; KKPKP; Mailhem Engineers; Enprotech Solutions; Pune Municipal Corporation Department of Solid Waste Management and Department of Transportation; Institute of Natural Organic Agriculture (INORA); Gangotree Eco Technologies. When other information needed for modeling was not available from primary sources, I
used and adjusted figures from relevant literature on markets, technologies, and industry. The results of the cost modeling are shown below.

6.1 Cost of Waste Collection

The total cost of door-to-door collection is estimated to be 1,628 Rs/ton. The majority of this cost comes from labor, which intuitively makes sense, given that the collection process mainly involves manual labor, rather than trucking or mechanization. We found that primary collection costs 296 Rs/ton, and that secondary collection costs 284 Rs/ton of waste transported; this means that the cost per ton for primary and secondary collection are similar. For both primary and secondary collection, the largest contributor to cost is operations and energy, specifically from the diesel consumption. The full cost of waste collection (when transporting waste to a centralized facility) is the sum of the costs from door-to-door collection, primary collection, and secondary collection. As shown in Figure 3, this combined cost of these three steps of collection is 2208 Rs/ton of waste, with the majority of this cost coming from door-to-door collection.

![Total Cost of Collection by Process Steps](chart.png)

**Figure 3**: The total cost of waste collection from curbside to a centralized facility.

6.2 Cost of Processing by Technology

Figure 4-7 on the following page show the results of cost modeling (broken down by cost elements) for landfilling, composting, anaerobic digestion, and pelletization.
Figure 4: The costs of landfilling by element.
Figures 5, 6, 7: The costs of composting, anaerobic digestion, and pelletization by element for a range of plant scales.
6.3 Net-Cost Comparison by Technology and Scale:

Table 2 summarizes the net cost per ton of managing organic waste using anaerobic digestion, composting, pelleting, and landfilling at different scales ranging from 0.1 to 200 tons per day. This net cost accounts for the revenue obtained for each technology. Because not every scale of plant could be modeled, some cells are left grey to indicate that the technology was not estimated for that particular scale. In this table, the general trend of cost decreasing with increasing scale (from left to right) can be seen across the technologies. Furthermore, by comparing the costs in each column, the different technologies can be compared at the same treatment scale. Landfilling costs are assumed to not vary with scale of treatment, as it is assumed the landfill is already constructed and will continue to have a large capacity.

As Table 2 shows, alternative organics management technologies used at small scales (less than 0.5 TPD) are more expensive than landfilling; however, if a facility of at least 0.5 TPD is used, anaerobic digestion is less expensive than landfilling. At the scale of 100 TPD, anaerobic digestion is 30% cheaper than landfilling. Pelleting also becomes less expensive than landfilling at the scale of 5 TPD. At the scale of 10 TPD, pelleting is 20% cheaper than landfilling. Furthermore, at the scale of 200 TPD, composting also becomes cheaper than landfilling.

The cost of treatment per ton was regressed on scale for each treatment technology, and the results (as well as the cost point estimates found from modeling) are displayed in Figure 8. The points at which the different-colored regression functions intersect roughly show the cross over points for where the costs of one technology changes from being more expensive to less expensive than another technology. From this plot, it can be seen that landfilling is lower cost than the other technologies implemented at the smallest scales (less than 0.5 TPD). At scale larger than 0.5 TPD, anaerobic digestion generally is the least cost option. At 5 to 10 TPD, pelleting becomes cost-competitive with anaerobic digestion (the costs are very close). Composting is generally more expensive than both anaerobic digestion and pelleting, but, at large scale, composting becomes cost-competitive with pelleting. Using the regression function for composting, composting becomes less expensive than landfilling at a scale of roughly 60 TPD.

Table 2: The net cost per ton of each treatment technology compared for a range of scales. Grey cells indicate that the cost was interpolated using other data points. The color-coding helps illustrate the range of values, with higher costs shown in warmer colors such as red, and lower costs shown in cool colors such as green. LAN = Landfill; AD = Anaerobic Digestion; COM=Composting; PEL=Pelletization.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Scale of Treatment (tons/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Anaerobic Digestion</td>
<td>7,375</td>
</tr>
<tr>
<td>Composting</td>
<td>6,438</td>
</tr>
<tr>
<td>Pelletization</td>
<td>5,776</td>
</tr>
<tr>
<td>Landfilling</td>
<td>2,929</td>
</tr>
<tr>
<td>Least Cost Technology</td>
<td>LAN</td>
</tr>
</tbody>
</table>
Figure 8: Plot of cost as a function of scale of treatment for anaerobic digestion, composting, pelletization, and landfilling. This plotted points includes cost estimates from the models, as well as from the regression analysis. The curves show the regression functions.

6.4 Key Findings from Economic Analysis

- Alternative organics management technologies used at small scales (less than 0.5 TPD) are more expensive than landfilling; however, if a facility of at least 0.5-2.0 TPD is used, anaerobic digestion is less expensive than landfilling. Composting at the scale of 200 TPD is also less expensive than landfilling. We are confident that these assertions are robust, given that the findings regarding comparison of net cost across technologies were generally not sensitive to variations in assumptions about the cost of capital, labor, secondary transportation, and the sale price of end-products.

- The cost per ton of waste managed using anaerobic digestion, composting, and pelletization decreases significantly with larger plant scales.

- Using treatment scales up to 10 TPD, the cost per ton is similar for pelletization and composting. However, if large scale plants of 100-200 TPD are used, then composting becomes significantly cheaper than pelletization.

- The cost per ton of door-to-door collection is much higher than the cost of primary or secondary collection. Door-to-door collection is a significant contributor to the cost of organics waste management from collection through disposal, as shown by the cost model results, broken down by element. Furthermore, sensitivity analysis shows that even if secondary collection costs are decreased on increased significantly, the least-cost technology for a given scale does not change.

- Apart from the cost of door-to-door collection, which was constant across all technologies, our analysis found that the major drivers of the total cost of anaerobic digestion, composting, and pelletization were labor and capital costs; for landfilling, the major drivers of the total cost were transportation and land.
Our cost modeling results indicate that a significant portion of the cost of processing waste using anaerobic digestion, composting, and pelletization is offset by revenues from the end-products of the processes. The ratio of revenue to cost was highest for composting. Sensitivity analysis shows that least-cost technology for a given scale does not readily change when the magnitude of revenue is increased or decreased. The ranking of technologies by cost is robust with regard to variation in sale price of finished compost or electricity, and is somewhat sensitive to increased sale price of pellets (which makes pelletization relatively cheaper).

7. Environmental Analysis

The focus of the environmental assessment of organic waste processes is on greenhouse gas emissions, or global warming potential (GWP). Global warming impact was selected as the focus because it is one of the most pressing environmental concerns, and because lifecycle assessment data on GWP of waste processes is relatively available. An extensive review of publications containing life cycle assessments of landfilling, composting, and anaerobic digestion of organic MSW was conducted in order to aggregate a set of estimates for GWP per ton of waste processed. I used a combination of data available from GaBi and EcoInvent databases to estimate the global warming impact of pelletization.

Using the results from the reviews of literature as well as analysis with life cycle assessment tools, I have plotted the range of GWP values for landfilling, composting, anaerobic digestion, and pelletization in Figure 9. The plot uses a box-and-whisker plot to show the interquartile range of the data set in the box; the ends of the whiskers illustrate the 2.5th and 97.5th percentiles. Because only one estimate of the environmental impact of pelletization was available, the GWP of pelletization is shown as a point, rather than a box-and-whisker plot. The spread (variation) in GWP estimates is largest for landfelling.

However, based on both the median values and interquartile ranges, the comparison across technologies indicates that composting, anaerobic digestion, and pelletization all have GWPs lower than that of landfilling. This analysis shows that organic waste technologies in order of lowest to highest GWPs are anaerobic digestion, pelletization, composting, and then landfilling; anaerobic digestion and pelletization are the only two technologies with a negative GWP, meaning that such treatment methods result in a net savings of greenhouse gas emissions.

![Global Warming Potential of Landfilling, Composting, Anaerobic Digestion, and Pelletization](image)
Figure 9: The range of values for the GWP for landfilling, composting and anaerobic digestion found from a review of the literature. The box and whisker plots show the 2.5 to the 97.5 percentiles.

Based on the values the GWP estimates for collection/transportation, the global warming potential per ton of waste managed at plants of different sizes was then determined, based on whether the system required (a) only door-to-door collection, (b) door-to-door and primary collection, or (c) door-to-door, primary, and secondary collection. The GWP per ton of waste, accounting for emissions from transportation for each technology and scale of treatment are listed in Table 3. These GWP values are used in the estimations of greenhouse gas emissions in the scenario analyses in the following section. As the table shows, for each treatment technology, the smaller scales of treatment have lower GWPs than the larger scales, as a result of lower transportation needs. Given that Pune’s landfill was already constructed at the periphery of the city, landfilling any amount of waste requires primary and secondary collection, and therefore the GWP per ton of waste landfilled does not vary with scale of treatment.

Table 3: The global warming potential (kg CO$_2$-eq) per ton of waste processed using each technology at various scales of treatment. These values include emissions from transportation.

<table>
<thead>
<tr>
<th>Treatment Technology</th>
<th>Scale of Treatment (tons/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1 TPD</td>
</tr>
<tr>
<td>Anaerobic Digestion</td>
<td>-51</td>
</tr>
<tr>
<td>Composting</td>
<td>38</td>
</tr>
<tr>
<td>Landfilling</td>
<td></td>
</tr>
</tbody>
</table>

8. Scenario Analysis

This section uses the estimates derived for net cost and global warming potential for different organic waste technologies at different scales of treatment to analyse the impacts of various waste management scenarios for Aundh ward in Pune, India. The social and labor impacts of a waste system (such as those addressed in Chapter 4) are also important to consider when making design and implementation decisions; but they more difficult to quantify and therefore are not directly incorporated into our scenario analysis. The level of centralization is used as one (albeit imperfect) proxy for social acceptability and potential inclusiveness of the informal sector; we anticipate that less centralized systems (i.e., more decentralized) are socially preferable for the informal sector.

In total, 24 waste management scenarios are analyzed for the system’s total cost, greenhouse gas emissions, space requirements, and level of centralization; six of the 24 scenarios are shown in Table 4. Aundh generates 47.5 tons/day of organic waste. Each scenario corresponds to a hypothetical system in which the 47.5 tons of organic MSW generated daily in Aundh ward are managed using one or a combination of the following technologies: landfilling, composting, anaerobic digestion, or pelletization. The scenarios also include a variety of scales of treatment, ranging between 0.1 and 100 TPD plants, for composting, anaerobic digestion and pelletization. The scenarios each involve the use of one or two treatment technologies, and one or two different plant sizes. The analysis contains scenarios representing the maximized use of a single technology, such that all of the organic waste is landfilled vs. all of the waste is composted vs. all of the waste is pelletized vs. all of the food waste is biodigested (the yard waste is assumed to be too woody for digestion).
Table 4: The total daily cost, daily greenhouse gas emissions, and space requirements, and level of centralization associated with 6 of the 24 modelled scenarios for managing 47.5 TPD of organic waste in Aundh ward.

<table>
<thead>
<tr>
<th>S#</th>
<th>Net Cost (Rs./Day)</th>
<th>GHGE (Kg CO₂-eq/day)</th>
<th>Spatial Footprint (m²)</th>
<th>Level of Centralization</th>
<th>Technology Used</th>
<th>Scenario Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>139,215</td>
<td>24,951</td>
<td>26,142</td>
<td>4</td>
<td>✓</td>
<td>All organics landfilled</td>
</tr>
<tr>
<td>S3</td>
<td>212,079</td>
<td>1,806</td>
<td>47,530</td>
<td>2</td>
<td>✓ 24@2</td>
<td>All organics composted, 2 TPD plants</td>
</tr>
<tr>
<td>S6</td>
<td>122,928</td>
<td>-1,749</td>
<td>8,428</td>
<td>2</td>
<td>✓ 22@2</td>
<td>Food waste A.D. in 2 TPD plants; yard waste rest is composted at 2 TPD plants</td>
</tr>
<tr>
<td>S11</td>
<td>99,662</td>
<td>-1,710</td>
<td>10,401</td>
<td>4</td>
<td>✓ 1@100 2@2</td>
<td>Food waste from Aundh A.D. in 100 TPD plant shared by two adjacent wards; yard waste is pelletized at 2 TPD plants</td>
</tr>
<tr>
<td>S14</td>
<td>110,840</td>
<td>-1,664</td>
<td>1,766</td>
<td>3</td>
<td>✓ 5@10</td>
<td>All organics pelletized, 10 TPD plants</td>
</tr>
<tr>
<td>S21</td>
<td>119,122</td>
<td>-2,074</td>
<td>4,572</td>
<td>3</td>
<td>✓ 9@5 1@5</td>
<td>Food waste A.D. at 5 TPD plants; yard waste pelletized at one 5 TPD plant</td>
</tr>
</tbody>
</table>

8.1 Least Space Alternatives
Of the 24 scenarios assessed, the least space-consuming system pelletizes all organic waste using 10 TPD plants (Scenario S14 in Table 4). A scenario in which a combination of one 10 TPD pelletization plant and a number of 5 TPD anaerobic digesters are used (S12) also requires a relatively small amount of space. A dense, overpopulated city or a city with very expensive property values might consider using pelletization as a space-saving method of organic waste management that avoids the need to transport waste to a far-away landfill.

8.2 Least-cost Alternatives
The lowest cost scenarios utilize large and medium scale anaerobic digesters to process most of the organic waste. In the top five least-cost scenarios, the majority of organic waste is anaerobically digested. In these scenarios, yard waste is pelletized, composted, or landfilled. The least-expensive of these involve digesting food waste in a 100 TPD plant that would be shared by two adjacent wards, and pelletizing the yard waste at 2 TPD plants (S11 in Table 4). Indian cities looking to minimize expenditures on organic waste management should consider using anaerobic digesters at the treatment scales 2 TPD or greater.
8.3 Largest GHGE Savings Alternatives
The scenarios with the largest GHGE savings (i.e., the smallest carbon footprint) all use anaerobic digestion to process all food waste. Four of the five scenarios with the largest GHGE savings anaerobically digest food waste in small scale plants (0.1-0.5 TPD plants), and use small- and medium-sized composting systems. The scenario with the largest GHGE savings scenario is somewhat centralized, using 5 TPD anaerobic digesters to process food waste and pelletization to process yard waste (S21 in Table 4). The combined use of anaerobic digestion and pelletization appears to offer the lowest GWP, given that both technologies have negative GWPs and that pelletization can be used to process woody material that cannot be biodigested. Generally speaking, the scenario analysis shows that systems that are relatively decentralized, utilizing plants with capacities no larger than 5 TPD, have the largest GHGE savings. A city looking to minimize its contribution to global warming could achieve significant reductions in emissions through the use of anaerobic digesters to process food waste at 0.5 and 5 TPD plants, combined with the use of pelletization to process yard waste. Such systems could save 750 tons CO$_2$-eq each year.

8.4 Decentralized vs. Centralized Alternatives
In Figure 10, the cost of each of the 24 scenarios as well as the greenhouse gas emissions of each of the 24 scenarios are plotted based on the level of centralization in the system architecture. As systems become more centralized, the net cost of organic waste management scenarios decreases, but the variation in cost between different treatment technologies also decreases (as shown by the smaller vertical scatter of the red points). This means that although somewhat centralized systems (using plants processing 100 TPD) do cost less, the lowest-cost highly decentralized systems are relatively close in value to the cost of the centralized systems. The upward trend the blue points plotted in the figure also demonstrates the finding that greater centralization of waste systems increase greenhouse gas emissions, because such systems involve increased transportation. These findings reveal that more decentralized organic waste systems tend to have a lower carbon footprint. Although the average cost of centralized systems are less expensive, decentralized systems are not strictly more expensive than centralized systems, due to the variation of technology choice; consequently, some highly decentralized systems are just as low cost as centralized systems. The difference in cost between the lowest-cost decentralized systems and lowest-cost centralized systems is relatively small. The lowest-cost decentralized system has a cost that is 18% higher than the lowest-cost centralized system.
Figure 10: Graph showing the relationship between systems’ level of centralization (further to the right on the x-axis indicates use of facilities with higher capacities) with net cost and with greenhouse gas emissions. Each point represents one of the scenarios.

8.5 Comparison of Costs and GHGE

In Figure 11, each of the 24 scenarios is plotted on a graph with the x-axis being net cost and the y-axis being greenhouse gas emissions. Each scenario is color coded indicate the technologies utilized in the particular system. Scenarios in the bottom left corner represent waste management scenarios with both small carbon footprints (sometimes negative) and relatively low cost. Scenarios in the upper left corner represent relatively low cost systems with high greenhouse gas emissions. Scenarios in the lower right corner represent high cost systems with low greenhouse gas emissions. As the graph shows, systems that use a combination of anaerobic digestion and composting, anaerobic digestion and pelletization, and anaerobic digestion and landfilling are the ones with both low cost and carbon footprints. The five scenarios with lowest combined cost and global warming impact include somewhat decentralized, somewhat centralized, as well as centralized systems. Each of these scenarios involves anaerobically digesting food waste in 2 TPD, 5 TPD, or 100 TPD plants. These findings suggest that anaerobic digestion, overall, is the technology with the best combination of cost and GWP performance.
Figure 11: Scatter plot comparison showing the relationship between systems’ cost and greenhouse gas emissions. Each point represents one of 24 scenarios. The color coding of the points indicates the treatment technologies employed in each scenario.

8.6 Comparison of Space and Costs

In order to understand what scenarios represent the best choice for cities forced to strictly consider space and cost, we have compared net cost and spatial footprint for the scenarios considered. In Figure 12, each of the 24 scenarios is plotted on a graph where the x-axis shows net cost and the y-axis shows total space needed for the system. The scenarios plotted in the bottom left corner represent systems which have relatively small spatial footprints and are relatively low in cost. The scenarios with the best combination for minimizing cost and spatial footprints highly utilize a combination of pelletization and anaerobic digestion; pelletization is a compact process that helps drive down the total spatial footprint, and anaerobic digestion offers economic efficiency to bring down the cost of the system. Space-constrained cities with tight budgets looking to find alternatives to landfiling should consider using a combination of anaerobic digestion and pelletization to process organic waste.
9. Conclusion

This project aimed to answer the question, what are the characteristics of a decentralized system that:

1. Is appropriate for the quantity and composition of waste generated in urban Indian?
2. Is cost-effective collecting and treating organic waste?
3. Reduces global warming impact (i.e., greenhouse gas emissions)?
4. Impacts stakeholders, including the informal sector, positively?

Although some economies of scale do create tradeoffs between cost and decentralization, the results of this project suggest that systems can be designed to process organic waste in a relatively decentralized way that is also relatively low in cost. Systems that utilize pelletization and anaerobic digestion plants processing 1-5 TPD appear to be appropriate for the urban Indian context given that they (1) have smaller spatial footprints, (2) are relatively cost-effective, (3) create a net savings in greenhouse gas emissions, and (4) create a decentralized system that can more easily involve and be compatible with the informal sector. Anaerobic digestion at the 2-5 TPD scale is especially effective for achieving greenhouse gas emission as well as cost savings, in comparison landfilling. Furthermore, given the interest so many stakeholders in Pune have in pursuing alternative organic waste management solutions over landfilling, it appears that anaerobic digestion – a well-established and proven technology – would also be socially accepted and politically supported.

It appears that composting, anaerobic digestion, and pelletization systems are all compatible with wastepickers access to organic waste and continued access to recyclables. Regardless of the scale used for such technologies, wastepickers could continue to conduct door-to-door collection;
furthermore, if training programs were put into place, some workers that are currently part of the informal sector could become employees at processing facilities. Landfilling organic waste also does allow wastepickers to continue door-to-door collection, however, due to the highly centralized nature of landfilling and the relatively low need for human labor in the landfilling process, it is unlikely that landfills could safely employ informal sector workers. Furthermore, because the landfilling process is easily tolerates non-biodegradables, landfilling waste creates the additional risk that recyclable material (valued by wastepickers) is collected and mixed with organic waste; this is much less of a risk if the city uses technologies specifically designed for (and limited to) processing source-segregated organic waste. Given that landfills are hazardous places often fenced off from access by wastepickers, continued or expanded use of landfilling as a method for handling organic waste could negatively impact the informal sector’s ability to generate revenue and could make landfilling any type of waste less desirable to the informal sector.